Will be published in **Astronomy Letters, 2009, vol. 35, No. 7.**

Detection of heavy-metal lines in the spectrum of the circumstellar envelope of a post-AGB star

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Abstract. Splitting of the strongest absorption lines with a lower-level excitation potential $\chi_{\rm low} < 1$ eV has been detected for the first time in the optical spectra of the post-AGB star V354 Lac obtained with a spectral resolution R = 60000 at the 6-m telescope BTA. Analysis of the kinematics shows that the short-wavelength component of the split line originates in the star's thick gas–dust envelope. Disregarding the splitting of strong lines when the chemical composition is calculated leads to overestimated excess of s-process elements (Ba, La, Ce, Nd) in the stellar atmosphere. The profiles of strong absorption lines have been found to be variable. The available radial-velocity data suggest the absence of any trend in the velocity field in the atmosphere and circumstellar envelope of V354 Lac over 15 years of its observations.

1. Introduction

The cool variable star V354 Lac = HD 235858 identified with the infrared source IRAS 22272+5435 is one of the most interesting candidates for protoplanetary nebulae (PPN). Intermediate-mass stars that evolve from the asymptotic giant branch (AGB) to a planetary nebula are observed at the short PPN phase of evolution. The initial masses of these stars lie within the range 3–8$\mathcal{M}_\odot$. The evolution of intermediate-mass stars was described in detail, for example, by Blocker (2001), while we will recall only the main points of this process. Having passed through the successive core hydrogen and helium burning phases of evolution, these stars underwent great mass loss in the form of a strong stellar wind at the AGB phase (the mass loss rate reached $10^{-4}\mathcal{M}_\odot$/yr). Since the bulk of the stellar mass is lost, a post-AGB star is a degenerate carbon–oxygen core with a typical mass of about 0.6$\mathcal{M}_\odot$ surrounded by an expanding gas–dust envelope. The interest of astronomers in PPN stems, first, from the possibility of studying the history of mass loss via a stellar wind and, second, from the unique opportunity to observe the result of stellar nucleosynthesis, mixing, and dredge-up of nuclear-reaction products to the surface layers during the preceding evolution of the star.

V354 Lac was one of the first PPN candidates with feature at 21 μ in the infrared spectrum whose atmospheres exhibited large overabundances of carbon and

s–process elements (Zacs *et al.* 1995). The energy distribution of V354 Lac has a double-peak pattern typical of PPN, with the total energies emitted by the star in the visible wavelength range and by the circumstellar envelope in the infrared being almost identical (see Fig. 4 in Hrivnak & Kwok (1991)). In the group of related objects, V354 Lac stands out by significant photometric variability. According to Hrivnak and Kwok (1991), the B and V magnitudes for two epochs of observations differed by $0\overset{m}{.}72$ and $0\overset{m}{.}84$, respectively.

Secular variability of the main parameters detected in several PPN stimulates a spectroscopic monitoring of the most probable PPN candidates. For example, we detected spectroscopic variability of the optical counterparts of the sources IRAS 01005+7910 (Klochkova *et al.* 2002a), IRAS 05040+4820 (Klochkova *et al.* 2004a), and IRAS 20572+4919 (Klochkova *et al.* 2008) and found a trend in the effective temperature $T_{\rm eff}$ for the star HD 161796 = IRAS 17436+5003 (Klochkova *et al.* 2002b). Here, it is also pertinent to recall the evolution of the parameters and chemical composition of the famous highly evolved star FG Sge observed for more than a century (see the review by Jeffery and Schonberner (2006) and references therein). In this paper, we present the results of high spectral resolution observations of V354 Lac for the epoch 2007–2008 and compare the new data with previous ones. Our main goal is to reveal probable spectroscopic variability and peculiarity of the spectrum as well as to study the velocity field in the atmosphere and circumstellar envelope of the star.

2. Observations and spectroscopic data reduction

We obtained new spectroscopic data for V354 Lac with the NES echelle spectrograph (Panchuk *et al.* 2007) at the Nasmyth focus of the 6-m telescope BTA of the Special Astrophysical Observatory. The observations were performed with a large-size 2048×2048-pixel CCD array and an image slicer (Panchuk *et al.* 2007). The spectral resolution was R = 60000. The first spectrum (JD = 2454170.58) was taken in the wavelength range 4514–5940 Å, the next two spectra (JD = 2454225.51 and 2454727.35) were taken in the longer wavelength range, 5215–6690 and 5260–6760 A, respectively. One-dimensional spectra were extracted from two-dimensional echelle frames using the ECHELLE context of the MIDAS software package modified by Yushkin & Klochkova (2005). Cosmic-ray particle hits were removed by a median averaging of two successive spectra. The wavelength calibration was performed using the spectra of a hollow-cathode Th–Ar lamp. The heliocentric radial velocities $V_\odot$ estimated from these spectra and listed below in the table were found using the DECH 20 package (Galazutdinov 1992).

3. Discussion of results

3.1. Peculiarity of the Spectrum

Hrivnak (1995) classified V354 Lac as a G5 Iap supergiant. The main features of its optical spectrum were pointed out even in the firrst works with a low spectral resolution. Hrivnak (1995) and Hrivnak & Kwok (1991) found that, compared to the spectrum of a normal supergiant with a similar temperature, the spectrum of

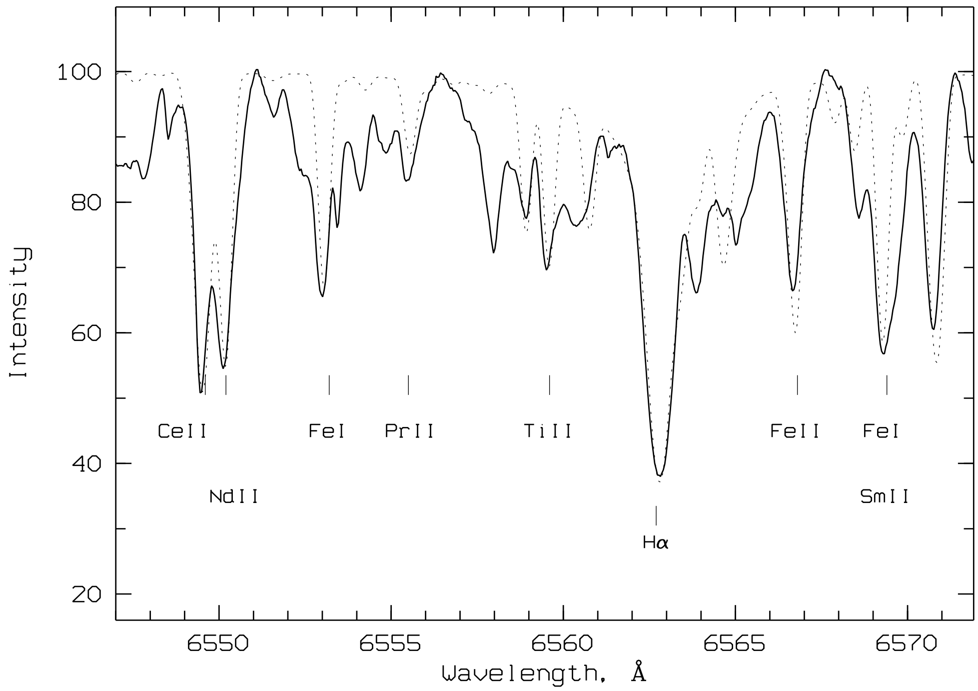

Fig. 1. Part of the spectrum for V354 Lac near Hα. The dotted line indicates the theoretical spectrum calculated with $T_{eff} = 5650$ K, $\log g = 0.2$, $\xi_t = 5.0$ km/s, and the elemental abundances derived previously (Klochkova *et al.* 2009). The telluric spectrum was not subtracted.

V354 Lac exhibits a weaker Hδ line, stronger Ba II lines, and CN, C_2 and C_3 molecular absorption bands. Most of the listed features are also observed in our 2007–2008 spectra. In particular, we used rotational lines of the Swan C_2 (0;0) band, with the head at 5165.2 Å, to determine the expansion velocity of the envelope (for more detail, see below).

The low-excitation Ba II lines are the strongest absorption features in the spectrum of V354 Lac; their equivalent widths W_λ exceed 0.6 Å. The absorption features of other ions of s-process elements (La, Ce) are equally strong; their W_λ >0.3 Å. Figure 1 shows the Hα line profile that consists of an absorption component with a narrow core and broad wings for JD = 2454225.5. As we see from the figure, the observed Hα line profile in the spectrum of V354 Lac agrees with the theoretical one calculated with its fundamental parameters $T_{eff} = 5650$ K, $\log g = 0.2$, $\xi_t = 5.0$ km/s, and the elemental abundances derived by Klochkova *et al.* (2009). Thus, we found no weakening of this line, as expected from the results of Hrivnak (1995). This is indicative of the line formation in the stellar photosphere and a weak contribution from the envelope. The positions of the Hα and Hδ cores differ by 2–4 km/s from the averaged velocity measured from photospheric metal lines.

The high spectral resolution allowed us to detect another, previously unobservable feature of the optical spectrum for V354 Lac — splitting of the cores of the strongest heavy-metal lines. This splitting is clearly seen from Fig. 2 for the profile of the Ba II λ 6141 Å line with an equivalent width $W_\lambda \approx 1$ Å. Such splitting (or asymmetry of the line profile due to the extended blue wing) is also observed for other Ba II

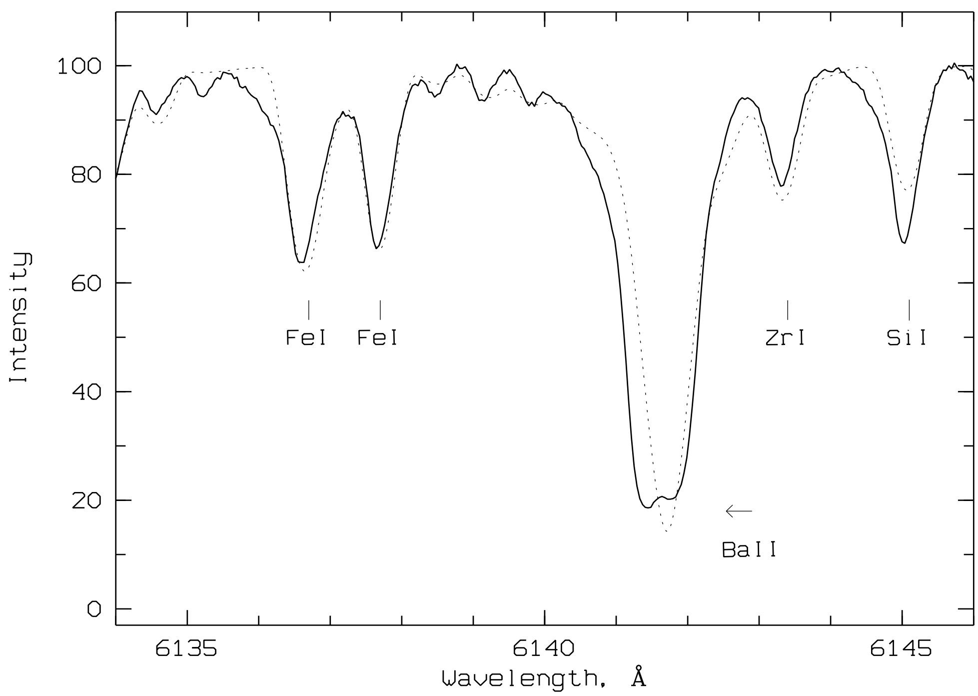

Fig. 2. Part of the spectrum for V354 Lac. The Fe I 6136.7, Fe I 6137.7, Ba II 6141.7, Zr I 6143.4, and Si I 6145.1 Å lines are marked. The dotted line indicates the theoretical spectrum calculated with Teff = 5650 K, $\log g = 0.2$, $\xi_t = 5.0$ km/s, and the elemental abundances derived previously (Klochkova *et al.* 2009).

lines (λ 5435, 5853, and 6496 Å) and for such strong lines as YII 5402 Å, La II 6390 Å, and Nd II 5234 Å and 5293 Å. The lines of these heavy elements in the spectrum of V354 Lac are enhanced to an extent that their intensities are comparable to those of HI lines (compare Fig. 1 and 2). Asymmetry is clearly seen, for example, in the Ba II 5853 line profile (Fig. 3). This figure, which shows the Ba II 5853 and 6141 Å lines for several dates of observations, also illustrates variability of the profiles of strong lines. Unfortunately, the Ba II 6141 Å line was recorded only for two dates, but the profiles may be said to be variable even in this case.

All of the lines with detected core splitting (or profile asymmetry) are distinguished by low lower-level excitation potentials, $\chi_{\rm low} < 1$ eV. Obviously, the strong low-excitation lines originating in the upper layers of the stellar atmosphere are affected by the gas envelope. As an illustration, Fig. 4 compares the Ba II and La II lines in the spectrum taken on one date (JD = 2454225.51).

As an example, let us consider the picture of core splitting for heavy-element lines in more detail for the Ba II 6141 Å line, for which this effect is most pronounced. The separation between the absorption components of the Ba II 6141 Å line is about 35 km/s. The short-wavelength component coincides in position with the circumstellar component of the NaD1 profile (see Fig. 5). This coincidence confirms that, apart from the photospheric component, the complex Ba II 6141 Å line profile contains a component originating in the circumstellar envelope. At an insuficient spectral resolution, the intensity of the envelope components is added to

the intensity of the components originating in the atmosphere. As follows from Zacs *et al.* (1995), Reddy *et al.* (2002), and Klochkova *et al.* (2009), large overabundances of heavy elements synthesized during the s-process are observed in the atmosphere of V354 Lac. Because of core splitting (and/or asymmetry), the heavy-element abundances derived from strong absorption lines in the spectrum of V354 Lac turn out to be overestimated by about 0.2–0.4 dex at an unsufficient spectral resolution.

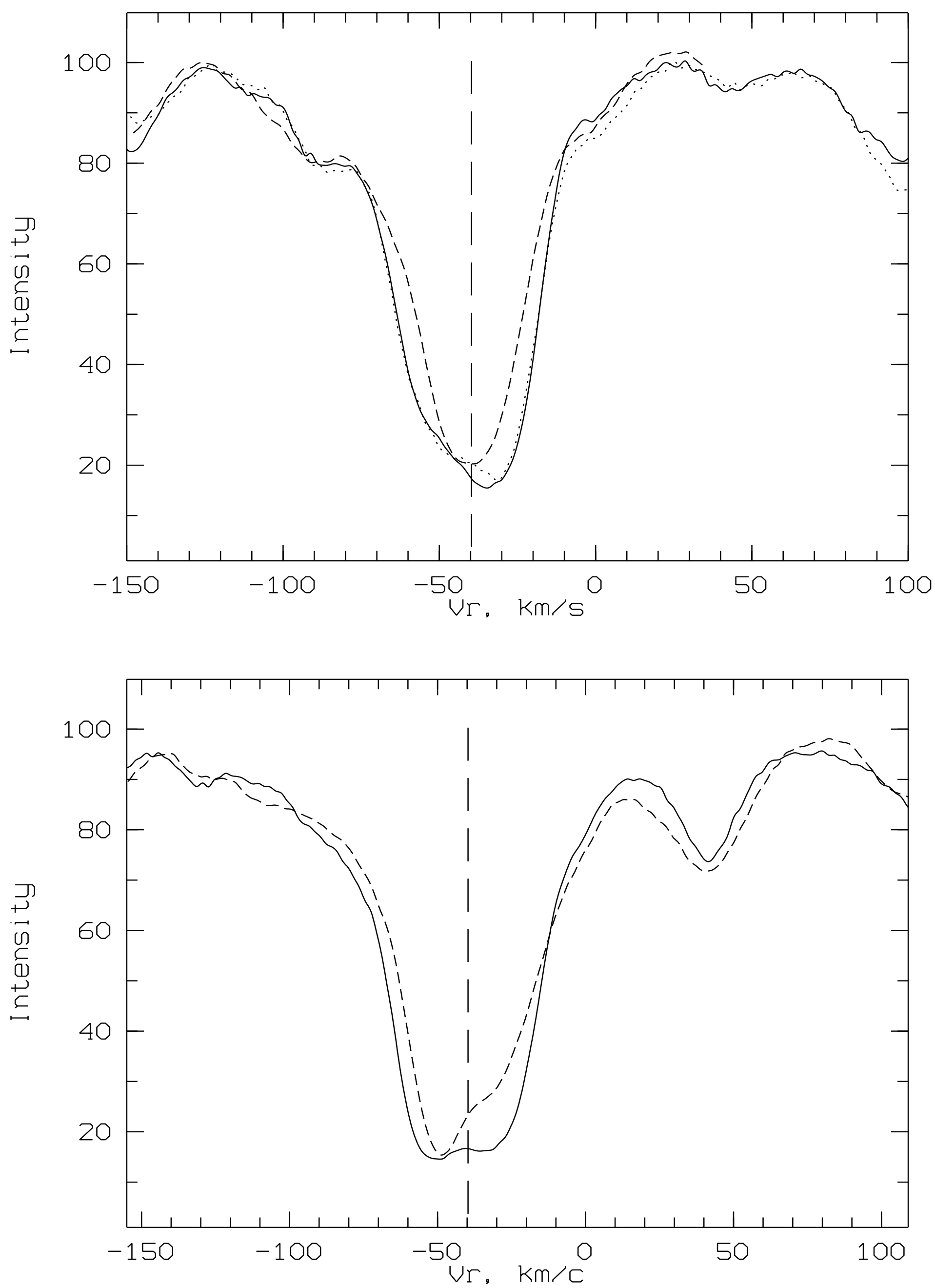

Fig. 3. Variability of the Ba II 5853 (a) and 6141 Å (b) line profiles in the spectra of V354 Lac: the dotted, solid, and dashed lines are for JD = 2454170.6, JD = 2454225.5, and JD = 2454727.4, respectively. The systemic velocity is indicated by the vertical dashed line.

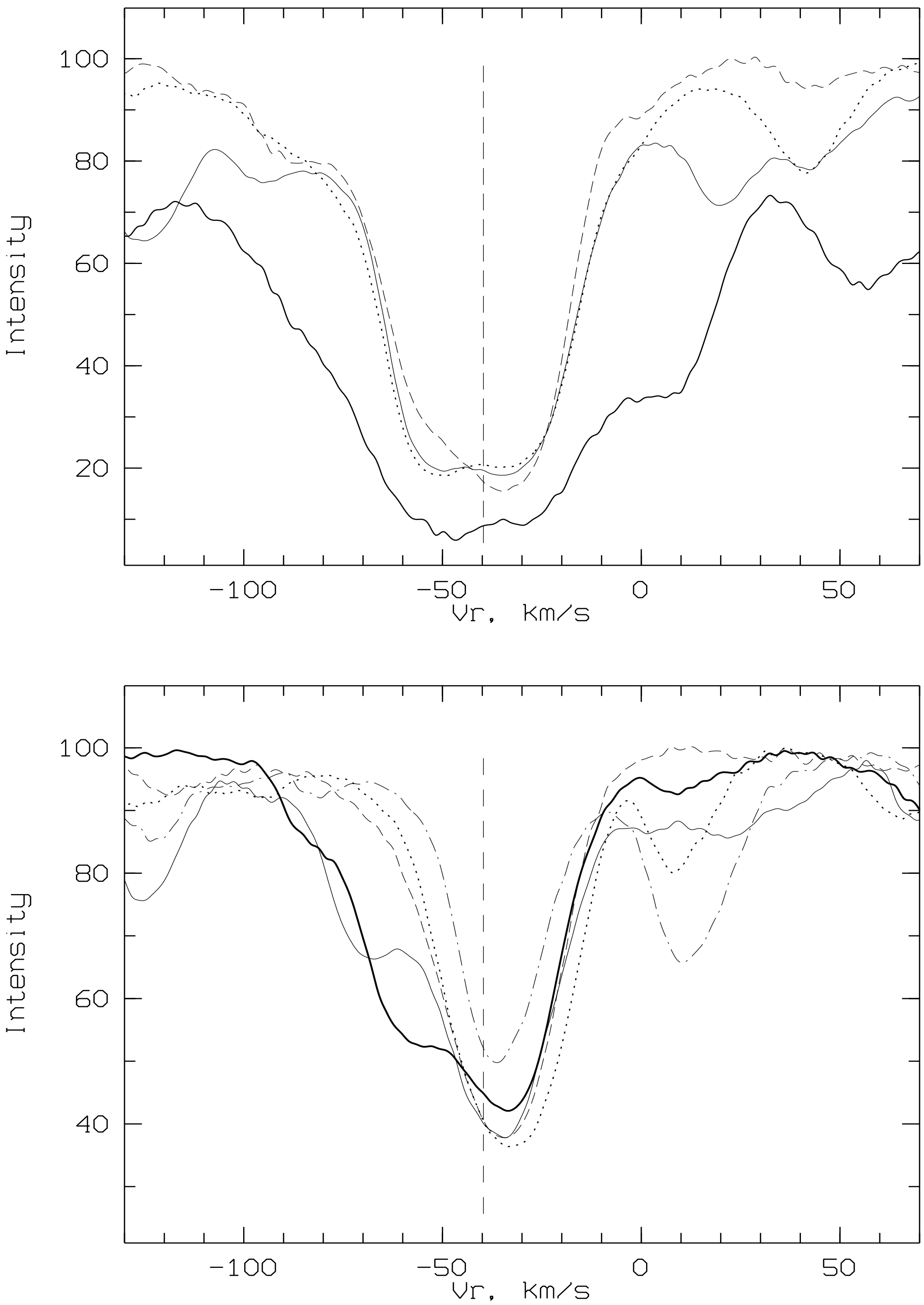

Fig. 4. (a) Ba II line profiles in the spectrum of V354 Lac on JD = 2454225.5: the thick solid, thin solid, dashed, and dotted lines represent Ba II 4934 Å, Ba II 6496 Å, Ba II 5853 Å, and Ba II 6141 Å, respectively. (b) The same as in panel (a) but for the La II lines: the thick solid, thin solid, dash–dotted, dashed, and dotted lines represent La II 6390 Å, La II 6320 Å, La II 5808 Å, and La II 6526 Å and La 6262 Å, respectively. The systemic velocity is indicated by the vertical dashed line.

The abundances derived from moderate-intensity lines will be more realistic. We emphasize that such a complex profile, which, apart from the photospheric and interstellar components, also contains the circumstellar component, has been previously observed only for the NaI D doublet lines. In particular, this is also true

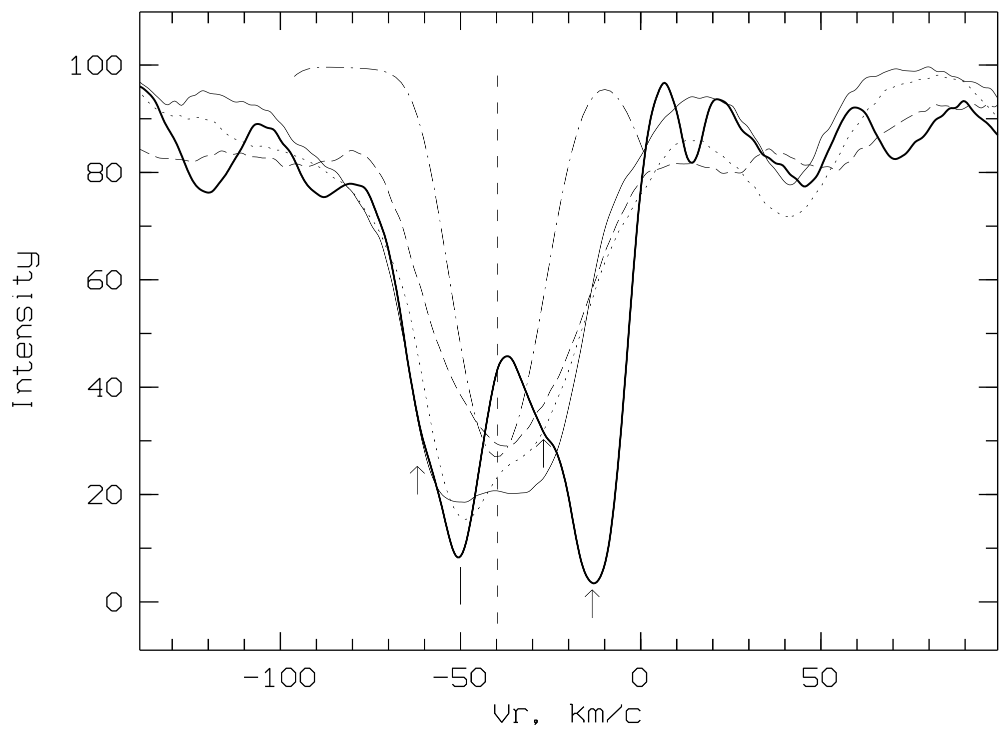

Fig. 5. Selected line profiles in the spectrum of V354 Lac: the thick curve represents the NaD1 line of the sodium doublet; the thin and dotted curves represent the Ba II 6141 Å line for two dates; the dashed curve represents Hα. The dash–dotted line indicates the theoretical NaD1 profile calculated with $T_{\rm eff} = 5650$ K, $\log g = 0.2$, $\xi_{\rm t} = 5.0$ km/s, and the elemental abundances from Klochkova *et al.* (2009). The vertical dashed line indicates the systemic velocity; the arrows mark the interstellar components; the vertical bar marks the circumstellar component of the NaD1 line.

for the star V354 Lac under study. Reddy *et al.* (2002) distinguished the circumstellar component in the NaI D lines. The circumstellar absorption features of the NaI D lines were also identified in the spectrum of the well-studied post-AGB star HD 56126 (Bakker *et al.* 1996; Klochkova & Chentsov 2007). In addition, manifestations of the gas–dust circumstellar envelope in the form of emission components in the NaI D lines are known. As an example, we present the spectra of the protoplanetary nebula V510 Pup identified with the infrared source IRAS 08005−2356 (Klochkova & Chentsov, 2004), the two-lobe nebula Egg = AFGL 2688 (Klochkova *et al.* 2004b), and the semiregular variable QY Sge = IRAS 20056+1834 (Rao *et al.* 2002; Klochkova *et al.* 2007c). In our study, we have found a manifestation of the envelope in heavy-metal lines for the first time.

3.2. Radial velocities

Metal lines. To determine the mean heliocentic radial velocity $V_\odot$, we measured the positions of a large number (about 300) of minimally blended absorption lines in the spectra of V354 Lac. The lines were selected using a spectral atlas for the post-AGB star HD 56126, which may be considered as a canonical post-AGB object (Klochkova *et al.* 2007a). The atlas was compiled by Klochkova *et al.* (2007b) from

Table 1. Heliocentric radial velocities $V_\odot$ for three epochs of observations measured from various spectral features. The number of measured lines is given in parentheses. The first row provides $V_\odot$ derived from the spectrum taken at BTA with the Lynx spectrograph (Panchuk *et al.* 1999, R = 25000). The last row presents the data from Reddy *et al.* (2002)

JD=24...	$V_\odot$, km/s				
	metals	HI	NaD		C_2
			blue	red	
48850.51	−38.2	−41.1 Hα	−50.2	−13.2	−50.5(8)
54170.58	−40.1	−45.1 Hβ	−50.6	−14.4	−50.1(21)
54225.51	−38.4	−37.2 Hα	−51.1	−13.4	
54727.35	−38.0	−34.6 Hα	−51.6	−14.0	
20.08.2000	−42.4 (Reddy *et al.* 2002)				

echelle spectra taken with the same NES spectrograph of the 6-m telescope. The blending level in the spectrum of V354 Lac is higher than that in the spectrum of HD 56126 because of the later spectral type of the star (the effective temperature of HD 56126, $T_{\rm eff} = 7000$ K, was determined by Klochkova (1995)) and because of the splitting and asymmetry of many lines. Due to enhanced blending, the accuracy of measuring $V_\odot$ using one line (rms deviation σ) is about 2 km/s from our 2007–2008 spectra. The radial velocities of V354 Lac measured from the set of spectral features are listed in the table. Here, the second column gives the mean V measured from metal lines. The next columns give $V_\odot$ measured from the Hα and Hβ lines, the components of the NaD lines, and the rotational lines of the Swan C_2 molecular band.

In addition to the data on the 2007–2008 spectra, the table includes our measurements of $V_\odot$ based on a spectrum taken previously at BTA with the Lynx echelle spectrograph (Panchuk *et al.* 1999) with resolution R = 25000. The last row gives the mean $V_\odot$ from Reddy *et al.* (2002). As follows from the longterm observations by Hrivnak and Lu (2000), the radial-velocity variability amplitude and period for V354 Lac are typical of PPN: the radial velocity varies within the range $(-34 \div -41)$ km/s with a period of $127^{\rm d}$. All of the mean $V_\odot$ derived using metal absorption lines from the table lie within this range of variability.

Molecular spectrum. Apart from the infrared excess and reddening, the presence of a gas–envelope around the central star of PPN also manifests itself in features of the optical spectra. Since the molecular bands can be formed in the atmosphere of a star with a temperature $T_{\rm eff} < 3000$ K, it is obvious that for a G5 star, the molecular bands are formed in the circumstellar envelope. Vibrational Swan C_2 molecular bands are observed in our spectra of V354 Lac. The high spectral resolution makes it possible to measure accurately the positions of the rotational lines of the Swan (0;0) band. Using the rotational-line wavelengths from the electronic tables to the paper by Bakker *et al.* (1997), we measured the positions of 21 rotational lines of the Swan (0;0) band and determined the mean radial velocity in the band-formation region, $V_\odot(0;0) = -50.1 \pm 0.2$ km/s. Because of their narrow profiles compared to the photospheric lines, the rotational lines of the Swan (0;0) band are easily distin-

guished in the spectrum. Therefore, the position of one line can be measured with an accuracy of about 0.8 km/s, which is much better than that for photospheric absorption lines. Since the Swan (1;0) band in the short-wavelength part of the spectrum 4712–4734 Å is strongly blended by photospheric lines, the measurement accuracy is much lower, $V_\odot(1;0) = -50.0 \pm 1.0$ km/s.

The shift of circumstellar features relative to the systemic velocity allows the expansion velocity of the corresponding envelope regions to be determined. Fong *et al.* (2006) derived the systemic velocity $V_{lsr}^{sys} = -27.5$km/s ($V_\odot^{lsr} = -39.7$ km/s) of the source IRAS 22272+5435 from the position of the center of the CO (1–0) profile. In contrast to the emission CO lines formed in an extended envelope that expands in all directions, the observed absorption lines of molecular carbon are formed in the part of the envelope located between the star and the observer. As a result, we obtain the velocity of the Swan-bands formation region relative to the stellar center, $V_{exp} = 10.8$ km/s. This value, which may be considered as the envelope expansion velocity derived from optical spectra, agrees well with the the expansion velocity for IRAS 22272+5435, $V_{exp} = 10.8 \pm 1.1$ km/s, from the catalog by Loup *et al.* (1993), who collected numerous observations of circumstellar envelopes in CO and HCN molecular bands. Note that the envelope-expansion velocity for IRAS 22272+5435 is typical of the circumstellar envelopes of post-AGB stars (see, e.g., Loup *et al.* 1993).

The heliocentric systemic velocity $V_\odot^{lsr} = -39.7$ km/s agrees well with the mean velocity of the star inferred from metal lines. This agreement indicates that there is no secondary component in the system of IRAS 22272+5435 or, to be more precise, there is no secondary component with a stellar mass. This is a nontrivial result, since the chemical evolution, mixing, and dredge-up of nuclear-reaction products to the surface layers of the stellar atmosphere, the outflow of matter, and the formation of envelope morphology can proceed in a special way in the presence of a secondary companion.

Taking into account the galactic CO velocity maps (Vallèe 2008), the galactic coordinates ($l = 103\overset{\circ}{.}3$, $b = -2\overset{\circ}{.}51$), and the systemic velocity $V_{lsr}^{sys} = -27.5$km/s of IRAS 22272+5435, we can assume that the source is located between the local and Perseus arms.

NaD doublet. Both lines of the resonance NaI doublet in the spectrum of V354 Lac have a complex structure. As follows from the table and Fig. 5, which shows the D1 line profile, the doublet lines contain two strong absorption components whose positions correspond to the velocities $V_\odot = -50$ and -13 km/s. Obviously, the line with $V_\odot = -50$ km/s originates in the circumstellar envelope, where the circumstellar Swan C_2 molecular bands are also formed. The second component with ($V_\odot = -13$ km/s) is interstellar in origin. The presence of this interstellar component, $V_{lsr} \approx -27$ km/s, confirms our assumption that V354 Lac is located in the Galaxy farther than the local arm. According Georgelin and Georgelin (1970), the radial velocity in the local and Perseus spiral arms of the Galaxy are $V_{lsr} \approx -10$ km/s and -55 km/s, respectively. Thus, the distance to the Perseus arm d = 3.6 kpc derived by Foster & MacWilliams (2006) may be used as an upper limit for the source. By modeling the bolometric flux from IRAS 22272+5435, Loup *et al.* (1993) estimated the distance to the source to be d = 2.35 kpc.

As follows from Fig. 5, the blue wings of the NaI absorption features hint at the presence of poorly resolvable components in our spectra: $V_{\odot} \approx -57$ km/s ($V_{lsr} \approx -70$ km/s) and $V_{\odot} \approx -24$ km/s ($V_{lsr} \approx -37$ km/s).

Conclusions

Based on the optical spectra of the post-AGB star V354 Lac taken in 2007–2008 with the echelle spectrograph of the 6-m telescope with spectral resolution R = 60000, we detected core splitting or asymmetry (an extended blue wing) of absorption lines with lower-level excitation potentials $\chi_{low} < 1$ eV. This primarily applies to the strongest absorption lines identified with heavy-metal (Ba, La, Ce, Nd) ion lines. Allowance for the detected core splitting of the strongest absorption lines reduces the heavy-metal overabundances revealed previously by 0.2–0.4 dex.

The observed Hα line profile is in good agreement with the theoretical one calculated with the fundamental stellar parameters. This is indicative of the line formation in the stellar photosphere and a weak contribution from the envelope. The radial velocity of the star measured for two epochs of observations in 2007–2008 closely coincides, within the error limits, with the previously published data. This suggests that there are no velocity field variations in the atmosphere and circumstellar envelope of V354 Lac over the last 15 years of observations.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research (project No. 08–02–00072 a), the “Extended objects in the Universe” Basic Research Program of the Division of Physical Sciences of the Russian Academy of Sciences, and the “Origin and Evolution of Stars and Galaxies” Program of the Presidium of the Russian Academy of Sciences.

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